[0125] Depending on the desired embodiment, the equations and functions listed herein can be calculated on the host computer or on a local device processor (if present), or they can be split between the host processor and the local device processor. For example, the host can calculate every force value and stream the values to the interface device, as described in copending application Ser. No. 09/687,744, incorporated herein by reference. Alternatively, a device processor can calculate equation (15) or additional equations based on values and parameters passed to it by the host computer.

[0126] It should be noted that the equations (10) through (14) need only be calculated when the effects are changed, e.g., when there is a change to the commanded frequency of either waveform or when the threshold frequency is changed. Equation (15), however, calculates the actual position of the inertial mass of the actuator assembly for each cycle of output, e.g. at 1 kHz. Thus, the method including equation (15) can be computationally intensive, especially for those embodiments employing less sophisticated processors. Thus, in alternate embodiments, the equation (15) can be approximated or estimated with less complex computations. For example, the simplified sum of products method above can be used, although other methods can also be used to reduce the computational overhead.

[0127] Some force effects may require more frequent updates. For example, texture force effects provide output pulses or vibrations based on the position of the cursor/device with respect to predetermined areas spatially located in the workspace of the device and/or in the associated displayed graphical environment. In some embodiments, the frequency of output tactile sensations related to textures is dependent on the velocity of the user manipulandum in its workspace. If this is the case, then Equation (10) through Equation (15) can be calculated at the force update rate (e.g. 1 kHz). Or, the effective frequency can be assumed to be a value much less than f_c, allowing the normalized sum of products to be calculated using the texture magnitude, with the spatial position (e.g., x or y coordinate) substituted for time t in the equation, or velocity (multiplied by a constant) substituted for the frequency ω.

[0128] **FIGS. 14 and 15** show another example of outputting a sum of products waveform in which the low frequency waveform is closer to the threshold frequency f_c and the high frequency waveform is also closer to the threshold frequency. In this example, the low frequency waveform is at 10 Hz, while the high frequency waveform is at 20 Hz, with a threshold frequency at 15 Hz. In **FIG. 14**, graph **370** shows low frequency waveform **372** and high frequency waveform **374** as separate waveforms. The graph **376** of **FIG. 15** shows the resulting waveform **378** when using the normalizing and combining filter described above with these two waveforms **372** and **374**. As shown, the resulting waveform **378** roughly follows the low frequency waveform **372** with the large peaks and valleys, while the intermediate oscillations **380** create the high frequency that helps provide high strength tactile sensations.

[0129] Resonant Filter

[0130] A resonant filter is one in which the output signal of the filter is at or near the resonant frequency of the mechanical system, as explained above, and the commanded effect waveform appears as a modulation envelope. This approach can be used with actuators such as the actuator assembly described with reference to **FIG. 3**, or, more appropriately, with a piezo transducer or other type of actuator where the output magnitude has a high Q response around a definite frequency, i.e. those actuators having a definite frequency range in which the output sensations are quite strong as compared to sensations output at frequencies outside that range.

[0131] A resonant filter can be provided by using the normalized version of the envelope modulation described above. The resonant filter uses one resonant signal with a frequency at the resonant frequency of the system, but of low amplitude. The commanded waveform(s) are used to calculate the envelope only, which then modulates (multiplies) the resonant signal. This is similar to the sum of products method described above, but the resonant form of the filter is actually simpler in that the envelope for the normalized but uncombined filter in the calculation is the summation of envelopes times the resonant signal instead of the summation of the high passed signal times its modulation envelope. An example of a resonant filter output is shown:

$$f_{res}(t)=GA_rM_r\sin(\omega_r t+\phi_r)[1+\Sigma_{j,j}|B_r\sin(\omega_j t+\phi_j)|/(1-B_r)] \qquad (16)$$

[0132] Equation (16) differs from Equation (15) in that there is no summation of the two functions f(t) for the two (or more) effects; instead, only one f(t) is calculated, where the first term is the resonant signal and the second term is the summation of envelopes from the commanded waveform(s). Thus, the small portion of the low frequency signal that was passed by the high pass filter and appeared as part of the signal in the output waveform for the sum of products method, above, does not appear in the final waveform of the resonant filter. This causes the final waveform to be fully centered about the center of travel of the inertial mass of the actuator assembly (horizontal axis in the graph) at all times. This can allow stronger sensations in many embodiments, at the cost of slightly less low frequency information conveyed to the user.

[0133] Combining Two or More Commanded Tactile Sensations

[0134] The filters described above are mainly described with respect to providing a single desired low frequency tactile effect by combining it with a "dummy" high frequency effect. In other embodiments (n>2), multiple commanded effects can be combined with each other using the filters described above to achieve a strong output by the actuator assembly of **FIG. 3**. Oscillating inertial mass devices, such as the actuator assembly of **FIG. 3**, may have problems superimposing two or more different tactile sensations of different frequencies, especially when one sensation has a high frequency and the other sensation has a low frequency. For example, instead of using a predetermined high frequency signal, the two signals to be filtered and combined can be commanded as two simultaneous effects that are to be output. The commanded waveforms can have either a low frequency below the threshold frequency or a high frequency above the threshold frequency.

[0135] Furthermore, three or more effects can be combined, where the contributions of the effect waveforms are summed as indicated in the equations above. For example, if there are more than two effect waveforms, then a com-